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Efficient search under constraints and not working memory resources supports creative action emergence in a convergent motor task

Dominic Orth[a,b,c,*], Luke McDonic[a], Chris Ashbrook[a], John van der Kamp[a,b,c,d]

[a] Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, The Netherlands
[b] Amsterdam Movement Sciences, Amsterdam, The Netherlands
[c] Institute of Brain and Behavior, Amsterdam, The Netherlands
[d] Research Centre for Exercise, School and Sport, Windesheim University of Applied Sciences, Zwolle, the Netherlands

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ABSTRACT

Creative (original and functional) solutions to problems can be facilitated by guiding search behavior. According to cognitive models, when solving convergent tasks (tasks with few solutions), high available working memory (WM) resources and capacity can guide creative solution emergence via repeated (persistent) search within a solution subcategory. However, no clear associations have been found of WM capacity on creative outcomes when tasks require the individual to enact solutions in *divergent doing* tasks. This study further tested constraints on WM resources on search behavior and creative outcomes in a *convergent doing* task. Novices to combat sports were asked to repeatedly strike a target with the intent to achieve an individualized target force. In order to manipulate available WM resources, every ten strikes, participants were asked to recall and then retain a sequence of 5 digits (high load group: n = 21) or 2 digits (low load group: n = 21). The task constraints favored the functionality (or appropriateness) of a qualitatively distinct, non-obvious solution. Functionality was assessed using the force registered for each strike. Originality was assessed in terms of how infrequently actions occurred. Finally, search behavior was quantified based on changes in which limb was used and changes in which part of the limb was used from one strike to the next. There were no significant effects of WM load on creativity outcomes, solution search, or task success. Rather, task success was related to efficient search and creativity. Future research should focus on constraints (other than WM resources) that promote efficient search.

1. Introduction

Creative actions (i.e., actions that are original and functional) are thought to emerge from individuals' attempts to adapt to the (changing) environment to satisfy the current constraints (Orth, van der Kamp, Memmert, & Savelsbergh, 2017). The importance of such *adaptivity* (and subsequent creativity) is highlighted in daily activities, physical exercise, and sports which are characterized by a constant change in constraints (i.e., changes in interacting task, environmental, and individual constraints) (Hristovski, Davids, Araújo, & Passos, 2011; Orth et al., 2017; Withagen & van der Kamp, 2018). In this respect, Bernstein (1967, 1996), one of the pioneers of movement science, described motor skill as the ability to solve one or another type of motor problem, that is, as the

* Corresponding author at: Department of Health and Medical Sciences, Swinburne University of Technology, Victoria, Australia.
E-mail address: dorth@swin.edu.au (D. Orth).

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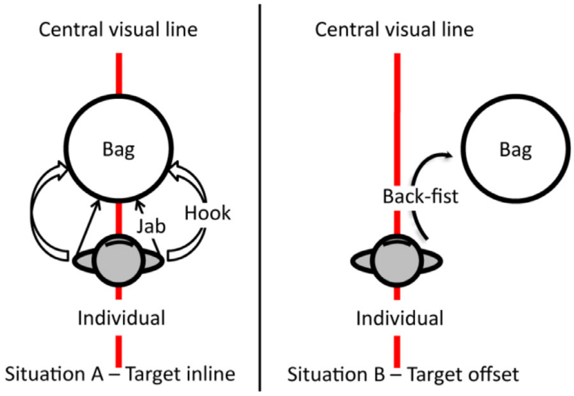

Fig. 1. Example of an 'action insight' (a back-fist with the right hand shown on the right) induced by manipulating constraints. Displacing the boxing bag to right of the individuals body midline can induce a transition from a hook to a back-fist action.
Adapted from Hristovski et al. (2011)

capacity to find adaptive solutions across circumstances that are never exactly the same. Accordingly, learning new motor skills implies a continuous search *to adaptively solve a motor problem* rather than acquiring one single optimized movement pattern (Araújo & Davids, 2011; Orth, van der Kamp, & Button, 2019; Savelsbergh, Kamper, Rabius, de Koning, & Schöllhorn, 2010). From this perspective, it is during this search process, wherein the individual aims to satisfy constraints, that creative actions emerge (Hristovski et al., 2011; Orth et al., 2017; Withagen & van der Kamp, 2018).

1.1. Emergence of creative action out of search for functional solutions under constraint

This study examines creative action emergence from the perspective of ecological dynamics (Araújo, Davids, & Hristovski, 2006; Warren, 2006). Following concepts from dynamical systems theory (Kijima et al., 2012) and ecological psychology (Withagen & van der Kamp, 2018), constraints are proposed as a key mechanism underpinning how perception, movement, and cognition are shaped and organized without being prescribed in advance (Newell, 1985, 1986; Orth et al., 2019). Constraints place boundaries on the available landscape of functional behavioral opportunities (i.e., affordances, Fajen, Riley, & Turvey, 2009) by influencing the relative stability (and related flexibility) of actions (Hristovski et al., 2011). Hence, constraints serve to influence (or structure) how the individual can functionally explore key information and the related affordances for action (Kimmel & Rogler, 2019; Ranganathan & Newell, 2013; Rietveld & Kiverstein, 2014).

To exemplify, Hristovski et al. (2011) described an experiment where individuals with basic boxing training were asked to strike a boxing bag. The bag was systematically moved from in front of the boxer to their left and right sides (this design is shown in Fig. 1). When the bag was in front of the boxer they would strike the bag with 'hooks' and 'straights' (Fig. 1 – left panel). As the bag was moved laterally (relative to their central body midline), at distances scaled by shoulder width, some participants switched from using straights or hooks and began to use the back of their hand (i.e., a 'back-fist') – which represented a qualitative reorganization of the limb trajectory (Fig. 1 – right panel). Hristovski et al. (2011, p. 195) referred to this as an 'action insight', suggesting that the technique emerged on the basis of how changing constraints increased the chance that movement system components could be (functionally) coupled in a new way. The example provided in Hristovski et al. (2011) highlights the often overlooked possibility that constraints (as designed by the researcher, coach, therapist, or learner) can liberate new and functional, creative actions (Orth et al., 2019).

However, for a given set of task and environmental constraints, not all individuals discover new or alternative actions. This has been shown across numerous motor learning experiments, where typically a sub-set of participants do not find motor solutions necessary for them to improve through practice (Delignières et al., 1998; Liu, Mayer-Kress, & Newell, 2006; Orth, Davids, Chow, Brymer, & Seifert, 2018; Pacheco, Hsieh, & Newell, 2017). To explain these observations, proponents of ecological dynamics posit important differences in the individuals' intrinsic dynamics (which reflect what the individual 'brings to the table' i.e., in terms of movement possibilities and preferences based on individual learning history), influencing the initial conditions with which a task is learned or can be approached (Renshaw et al., 2016). The intrinsic dynamics influence the (in)stability of the performance solutions that can be adapted by the individual with respect to a particular environment (Thelen, 1995). In this respect, individual constraints may be crucial for developing creative solutions since new solutions also mean departing from the stability of other solutions that may be already preferred before attempting to solve a motor problem (Kostrubiec, Zanone, Fuchs, & Kelso, 2012; Zanone & Kelso, 1992), or become highly preferred during the course of attempting to solve a particular problem (Hristovski et al., 2011). Unfortunately, not much is known about how constraints (individual or otherwise) influence search dynamics while solving motor problems. Nor for that matter has search, as it evolves overtime, been effectively linked to the emergence of creative actions (or action insights).

1.2. Personal constraints on solution search and subsequent creative behavior

Contemporaneous approaches examining personal constraints have focused on neuro-cognitive processes that might underpin creative solutions (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Moraru, Memmert, & van der Kamp, 2016). To do so, ideational solutions to problems have been related to neuro-cognitive capacities such as working memory (WM) (De Dreu et al., 2012) or to traits such as personality (De Dreu, Baas, & Nijstad, 2008; Fink & Woschnjak, 2011). This work has led to the notion that two internal cognitive pathways or systems (presumably exploiting different networks) independently develop creative solutions (Boot, Baas, van Gaal, Cools, & De Dreu, 2017; Lin & Lien, 2013; Nijstad, De Dreu, Rietzschel, & Baas, 2010).

One pathway underpins adopting different, unconventional, and potentially random perspectives during solution search and has been denoted as flexible creativity. Flexible creativity is typically quantified by counting the total number of different, mutually exclusive categories from which solutions emerge (De Dreu et al., 2012; Moraru et al., 2016). For example, taking the task described in Fig. 1 by Hristovski et al. (2011), exclusive categories could refer to using different limbs or qualitatively distinct 'techniques' (such as the 'hook', 'jab', or 'back-fist') to strike the bag (Orth et al., 2017). It has been argued that reduced cognitive control facilitates distant associations (Memmert, 2007). Hence, WM resources are said to play a minor role at best in flexible creativity or works to dis-associate solutions from one another (Dreisbach & Goschke, 2004; Nijstad et al., 2010). In the task depicted in Fig. 1, this might mean that if the individual had reduced WM resources, then a greater variety of different qualitatively distinct actions might be used to the solve the problem (for instance, switching to different limbs, which can be conceptualized as searching different 'coordination solutions', see Orth et al., 2017).

The second cognitive pathway reflects long periods of attentive effort searching within a single or narrow set of solutions and is denoted as a persistent creativity. Persistent creativity is measured by the average number of solutions derived from one and the same category (De Dreu et al., 2012; Moraru et al., 2016). In persistent creativity, previous solutions are memorized, monitored, and systematically varied and this exploits WM resources (Nijstad et al., 2010). Persistent creativity requires a brief memory of what has been done in previous attempts and followed by a manipulation of this information in generating a slightly different attempt. The more WM resources at the individual's disposal, the more systematic the search and the longer they can 'look back' (i.e., the more previous attempts are influential). Hence, WM constrains persistent creativity. Taking again the task described in Fig. 1 by Hristovski et al. (2011), persistent creativity would involve using the same limb or the same distinct 'techniques' to strike the bag. Unique variations in this technique might support a very effective (and therefore creative) strike. Exploration of variants of the same technique (or coordination mode) can be considered as searching different 'control solutions' (Orth et al., 2017).

In divergent thinking tasks, WM capacity is highly correlated to persistent creativity, but not to flexible creativity (Nijstad et al., 2010). Lin and Lien (2013) also reported that creative performance was hindered under high WM load during convergent thinking tasks (or 'insight problem-solving tasks'). This indicates that WM resources are important to solving tasks that require remembering previous attempts. However, in a divergent thinking task (where participants were asked to write down as many unusual uses for of a pair of chopsticks) creative performance improved with high WM load (i.e., indicating remembering previous solutions was less important for creativity in these tasks). According to Lin and Lien (2013), in tasks which are convergent-like, a rule-based resource limited cognitive system supports performance (and hence a high WM load reduces performance), whereas in divergent tasks, an associative and effortless cognitive system supports performance (where a high WM load can increase performance by inhibiting the alternative cognitive system).

1.3. Challenges to cognitive approaches to explaining creativity

A problem in the above mentioned studies, is that creativity is primarily looked at in terms of (a categorization of) ideas and outcomes, while the dynamics involved in arriving at solutions go unobserved. For instance, flexible creativity is denoted as the number of different 'between category' solutions expressed, irrespective of the order that they occur or how often an individual might switch amongst these in the effort to develop creative solutions (Withagen & van der Kamp, 2018). It is, therefore, not possible when only using summary outcome measures (such as the number of creative actions) to determine if success in divergent or convergent-like tasks is related to differences in search strategies (i.e., different patterns of search over-time) used to solve a given problem (Lin & Lien, 2013).

Following Orth et al. (2017), instead of different cognitive pathways producing creative solutions, observations related to persistence or flexibility might reflect different types of search processes to satisfy the constraints of the tasks at hand. That is, creative solutions emerge in an active process to satisfy constraints rather than prior to action (i.e., as ideation Guilford, 1956; Torrance, 1972). A key implication of this perspective is that design of tasks to assess creativity should move beyond the assumption that ideation is a sufficient condition for creative outcomes.

On the one hand, this is because constraints determine functionality. For example, a task where the individual's success is based on how hard they hit requires that a creative action is sufficiently forceful. On the other hand, unless the constraints allow for multiple solutions to support task success, there is no reason for an individual to vary (or for exploration to be particularly functional). That is, the notion that convergent tasks require a persistent creativity and divergent tasks require a flexible creativity (as suggested in, De Dreu et al., 2012; Lin & Lien, 2013) will not necessarily be the case. Rather the appropriateness of different search strategies will depend on whether modifying actions at coordination or control levels (or in a flexible or persistent like manner) serve to satisfy the constraints at hand (Orth et al., 2017).

Recently, Moraru et al. (2016) made a first attempt to examine search behaviors in a divergent doing task adapted from a task commonly deployed in physical activity settings (i.e., a motor task requesting participants to do as many different locomotion solutions as possible using an agility ladder). Whether actions reflected persistent or flexible creativity was determined by examining the stepping pattern used from one trial to the next. Specifically, 'between category solutions' included different modes of locomotion (skipping, hopping, stepping, walking with the hands etc.). Whereas 'within category solutions' were defined as using the same mode locomotion but with changes in the spatial patterning used. Hence, measures of flexibility (the total number of different categories used) and persistence (the average number of within-category solutions) could be operationalized in this task. Moraru et al. (2016) also attempted to assess flexible and persistent *search* – where flexible search was considered as manifest in frequent switching between categories and persistent search as in-depth exploration of a specific category (p. 5). For this, they determined the median length of bouts of consecutive solutions within a category. Longer bouts suggested increased persistent search, and shorter bouts suggested increased flexible search. This study observed no differences between high and low WM capacity conditions on the category of solutions produced or on the nature of search (i.e., flexible or persistent). Given these findings, it should also be addressed as to whether this is the case in convergent motor tasks as well (i.e., tasks with a single or few appropriate solutions, Orth et al., 2017). In theory, WM resources are critical in convergent tasks for creative solutions to be developed through a persistent search process.

1.4. The current study

The extant creativity research shows inconsistent results regarding the influence of WM resources on creative behavior. For example, as previously mentioned Moraru et al. (2016) reported no WM effect in a divergent movement task, whilst De Dreu et al. (2012) reported that semi-professional cellists performed increasingly creative improvisations with a higher WM capacity. Furthermore, links between search behavior and creative solutions remain poorly understood. To our knowledge, there has been no study conducted measuring the effect of WM in a convergent doing task. Furthermore, no studies have examined dynamics of search and how this is mediated by available WM resources in a convergent doing task.

The present study will examine whether available WM resources constrain the dynamics of search, task success, and creative actions. In reference to the cognitive dual-pathway model, we hypothesize that in a convergent doing task available WM resources promote persistent search and consequently the finding of successful and creative solutions. As proposed in Orth et al. (2017), we will utilize a kickboxing task, where one or few non-obvious solutions are functional (where functionality is explicit in the level of impact force participants can achieve) and examine search in terms of variability at the levels of coordination and control of actions (Fig. 2).

A key advantage of the proposed task (Fig. 2) is that functionality of each action can be assessed in terms of impact force as well as categorization of actions at levels of coordination (which limb is used to strike) and control (what part of the limb is used to strike) (see Methods for details). The variation at coordination and control levels while solving the motor problem will serve to indicate the extent to which search can be characterized as flexible (e.g., shown in the degree of switching across coordination solutions) or persistent (e.g., shown in the extent of switching of control solutions, whilst remaining within the same coordination solution) (Buszard, Reid, Krause, Kovalchik, & Farrow, 2017; Orth et al., 2017). The task is also consistent with an 'insight problem' where, following Dominowski (1995) the features of the task are: a) not beyond the capabilities of the problem solvers; b) the initial attempt is usually strong but wrong, which can create obstacles to finding the solution, and; c) solving the problem requires seeing the problem from a new perspective.

Finally, individuals will, while attempting to solve a convergent motor problem, perform a concurrent task to occupy available WM resources. Following, predictions from the dual-pathway model, we hypothesize that with more WM resources available (i.e., low WM load), search should be more persistent, and lead to a greater likelihood to develop creative solutions, whereas with less WM resources available, individuals should be more flexible in their search and be less likely to develop creative solutions because they

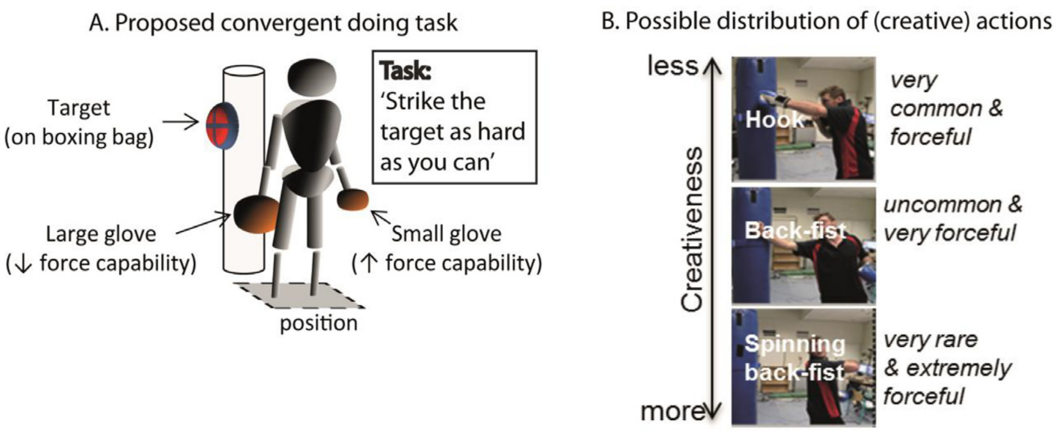

Fig. 2. Task design (A) and expected actions (B) adapted from Orth et al. (2017). The left panel shows the proposed task design where – by positioning a target on the left side of a boxing bag (relative to the individual's body midline) and making the left hand less functional (in terms of deliverable impact force) by use of a large padded glove – the search for alternative solutions can be facilitated. The right panel shows some potential actions that might emerge and their degree of creativeness (i.e., based on how forceful and uncommon they might be – pilot work confirmed these notions).

are inhibited in carrying out the in-depth search of (potentially) functional coordination solutions.

2. Methods

2.1. Participants

Forty-two right handed participants volunteered to undertake the study (males = 26, age = 26.8 ± 7.4, BMI = 23.35 ± 3.11) consisting of a 21 person sample per group (as predetermined by the power calculation assuming a large effect size: n = 42, β = 0.8, α = 0.05, r = 0.5) (Faul, Erdfelder, Buchner, & Lang, 2009). Participants were required to be injury free and have no previous experience in striking activities derived from martial arts. Participants were then assigned to either a high or low WM load group (the ordering of which was counterbalanced where every second participant recruited was assigned to the low WM load condition). Participants in all cases were naïve to the purposes of the experiment. The research project was approved by the institution's ethics committee, the Scientific and Ethical Review Board, Faculty of Behavioral and Movement Sciences, reference: VCWE-2016-228, and all participants were involved on the basis of prior informed consent.

2.2. Material and apparatus

The experiment was conducted in a laboratory, equipped with a hanging boxing bag (length = 176 cm, circumference = 112 cm, weight = 48.5 kg) which was instrumented to measure peak impact force (i.e., effectiveness of each strike). Following Buśko et al. (2016) the peak impact force of each strike was determined by computing the average accelerations of two internal accelerometers each positioned at the top and bottom of the bag and along the longitudinal axis of the bag center. As per Buśko et al. (2016), only the horizontal components of acceleration were included. The system's accuracy and reliability at the height of the target was verified by striking the target across a range of forces (400 N to 2000 N) with a strain gage instrumented hammer. These data were compared to the estimates of force provided by the accelerometers which showed very good reliability (across 48 strikes: $r = 0.95$, $p < .001$, one-tailed).

The instrumented bag system provided immediate feedback to participants of the most forceful strike overall (for that participant) and the current strike force both with respect to a target force. The target force was individually determined for each participant which was relative to their maximal punching force producing capability when striking with the right hand (described in: 'Procedure and Design'). The bag was positioned at the front and center of the striking area, which was denoted by tape on the ground (providing a stand-on-able area of 110 cm × 157 cm). A target to strike was positioned at the center and offset to the left side of the bag (Figs. 3 and 4). Participants were required to wear loose sports shorts, shin pads designed for kickboxing, one large sized standard boxing glove on the right hand (Width = 14 cm, Length = 24 cm long, Circumference = 43 cm) and one modified boxing glove on the left hand, which was significantly increased in size, containing soft foam padding and cotton to significantly reduce the effectiveness of the glove (Width = 23 cm, Length = 37 cm, circumference = 83 cm: shown in Fig. 4). The intention of this set up was to constrain the task such that it made the left hand less functional than the right hand. However, because the right limb was further from the target, use of the right hand to strike the bag reflected an action insight that would allow for a significantly more forceful strike to be realized. We chose to pad the non-dominant limb to ensure handedness was not an inhibiting reason for whether or not the right limb was used. A camera (Fujifilm FINEPIX XP80) was positioned 2 m away from the striking area, to record each interaction with the bag.

2.3. Working memory task

A random number generator was used to prepare two different sets of number sequences for each group. The same sets of numbers were used for each participant of the corresponding condition, each integer was a single digit ranging between 0 and 9. As per Moraru et al. (2016), for the high WM load condition, five digits were used, and for the low working WM load condition, two digits were used. Recall of two digits is assumed to strain the WM less than five digits in a recall task, whereas five digits does not tax all of the WM capacity (Baddeley, 2003; De Dreu et al., 2012; Moraru et al., 2016). To verify if participants were paying attention to the memory task and to gage their perception of difficulty relative to the striking task, participants were asked to rate these on a scale from 1 to 5 (this was done after the experiment was concluded).

2.4. Procedure and design

Upon entering the laboratory, written informed consent was obtained and participants' details were recorded. Participants were then equipped and performed a five-minute warm up consisting of shoulder rolls, abdominal twists, leg swings, and arm extension and flexion. They were then familiarized with the feedback system by striking it with a bat by the experimenter (a bat was used so as not to convey information about how to strike with the body). Following this, the height of the bag was changed relative to each participant such that the top of the target to strike was at the same height as each participant's clavicle, this was done so that kicking with the left leg was more difficult (i.e., assuming that most beginners would have difficulty kicking high).

Participants were then required to perform pre-test strikes (noting that participants were unaware of the purposes of the pre-test and also allowed participants to further accustom to the bag-feedback system). Specifically, participants were required to complete ten maximal strikes with the right hand against a target on the bag directly in front (a technique referred to as a 'straight punch'). The maximal score (SRmax) was used to calculate the target force (Ft) for the striking task, which was set at 1.8 times their straight right

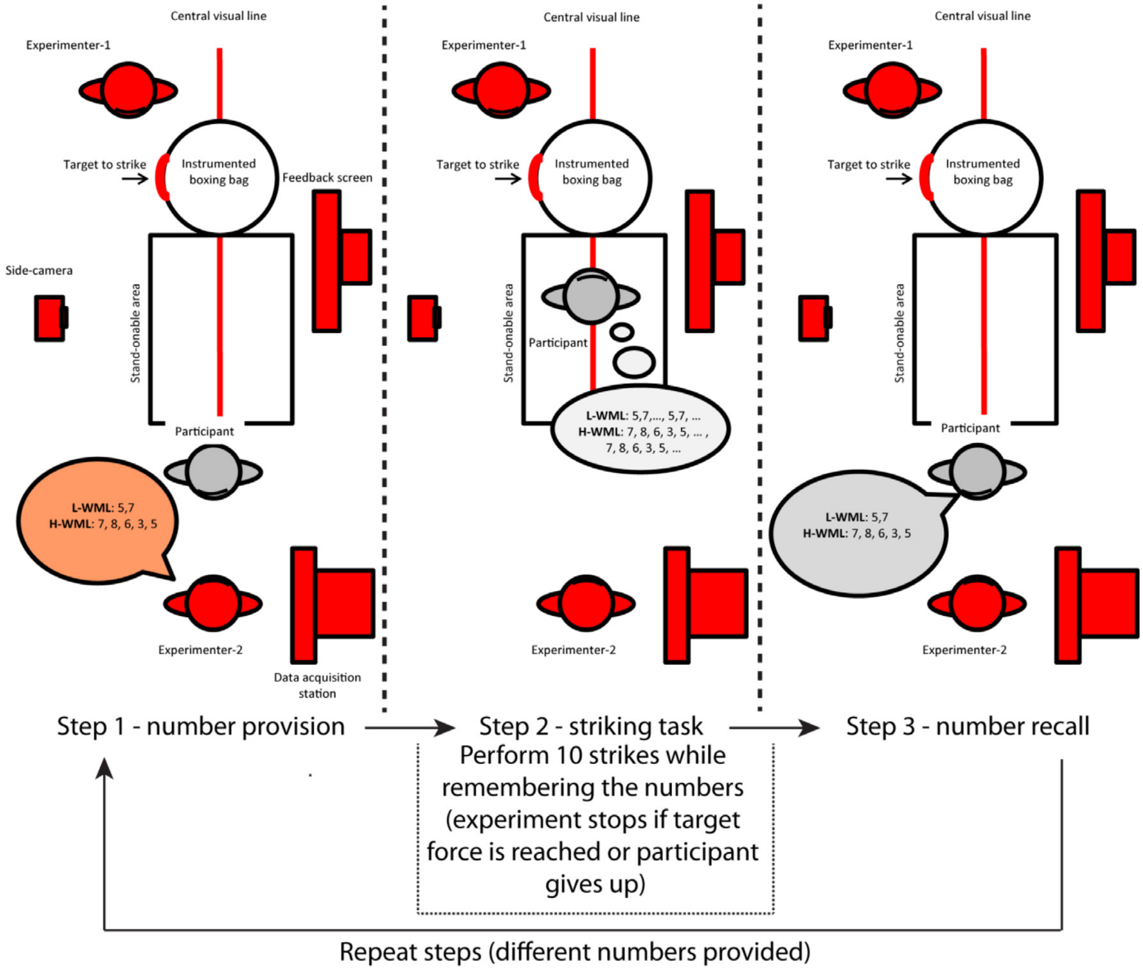

Fig. 3. Experimental set up and procedure. **H-WML** = high working memory load group. **L-WML** = low working memory load group.

max (i.e, Ft = SRmax * 1.8.). This coefficient was chosen based on pilot work, which showed (using Pearson's regression analysis) that the SRmax best predicted ($R^2 = 0.68$, $F(1,1) = 10.39$, $p < 0.05$, $N = 7$) the maximal force of the right handed back-fist (the technique representing the action insight intended to support task success) and where the mean ratio between the SRmax and the right back-fist max was 1.8 (SD = 0.57).

Following the pre-test, participants were then told they were to be involved in two tasks to be performed concurrently, i.e. the striking task and WM task. For the striking task each participant was instructed:

> "You are required to perform single strikes to the bag, following each strike, I will reposition the bag and indicate when you are able to strike again. You must stay within the striking area, which is marked out on the floor. You may use this space in any way you wish, and you can strike the bag with any part of your body. You must strike this target here, on the left. If you miss this target, the strike will be discounted. Your goal is to strike the target with enough power to beat the target threshold. You have unlimited strikes to achieve this, and as much time as you like. The study ends when you achieve the target threshold, or when you decide you have discovered the best way to do so."

In cases where participants decided to stop they were asked again if they were sure they wanted to stop. If they still wanted to discontinue, the experiment was halted (participants were never asked more than two times in succession if they wanted to continue). Participants were informed that the target force was achievable.

The WM task was then described as follows:

> "A string of two/five digits (dependent on group assignment) will be called to you. You must remember these digits and recall them in the correct order when requested. You will be informed of how many numbers were correctly recalled. You will then receive a new string of digits, and this process continues until you complete the striking task or choose to finish the experiment."

Participants were then asked if they fully understood the requirements and process of the experiment, as they were informed once the striking begins, no questions would be answered. The camera recording was then initiated and participants stepped into the

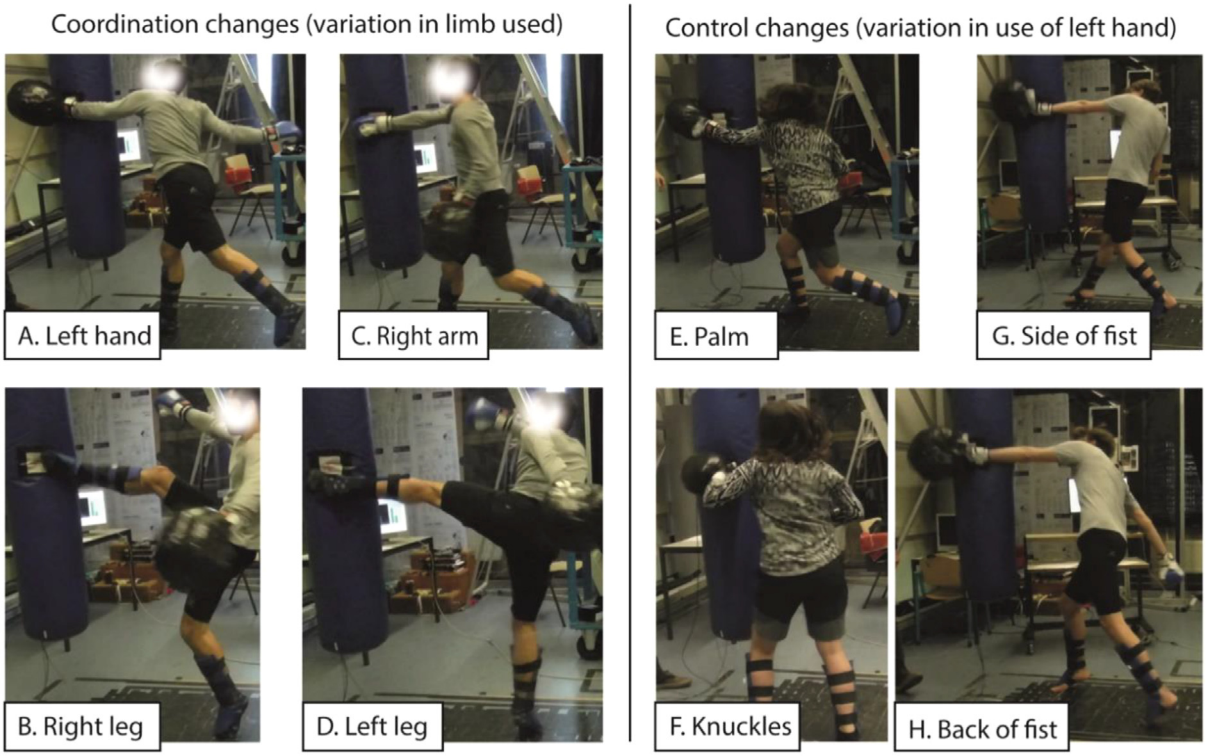

Fig. 4. Example of different coordination and control solutions for striking the bag. The left set of images (A-D) shows some of the different coordination solutions. The right set of images (E-H) shows some of the different control solutions with the left hand. Note the padded glove on the left hand reflects the equipment manipulation used to make the left hand less functional.

striking area and the first string of digits were called for memorization. Participants then completed the first ten strikes on the target and asked to recall the digits aloud. Feedback was provided of recall success, and then a new set of digits followed. This occurred after every 10th strike, until achieving their target force, or they decided to stop (steps are summarized to Fig. 3).

2.5. Data reduction and analysis

2.5.1. Identifying different coordination and control solutions

Alongside the impact force for each strike, notational analysis was conducted to obtain for each strike across all participants the coordination and control solution used. This involved labeling for each strike the limb used and the part of the limb used. In doing so, we operationally define each striking action at two levels of analysis, coordination and control.

On the one hand, different coordination solutions included the possibility that the left and right hands and feet, elbows and knees, or head were used. Additional coordination solutions were also identified during the course of the experiment and included: double hands (some participants used two hands at the same time to strike the bag); facing away from the bag (i.e., in some cases participants would strike the bag while facing in opposite direction of the bag), and; spin and strike (i.e., sometimes participants would strike the bag after completing a full 360 degrees spin around the bodies longitudinal axis). On the other hand, different control solutions included the possibility that changes in the part of the limb used reflected an effort to further optimize the coordination solution by exploring different ways of improving impact force with the same limb. The notational approach is detailed in Table 1.

To exemplify, in Fig. 4 Panels A and C show that changing the coordination solution from a left-handed strike to a right-handed strike involves a different coordination solution (the way angles/joints are constrained are clearly different, as can be seen in how the body is orientated with respect to the bag). This assumes that striking a boxing bag can be done in qualitatively different ways and that using a different limb will necessarily require qualitatively different spatial relationships between the end effector and the target on the boxing bag. In plain language different coordination solutions might correspond to different 'techniques' or 'action categories'. For example, different techniques that have been described previously in combat sports include jabs, hooks, uppercuts, roundhouse kicks (Hristovski et al., 2011; Hristovski, Davids, & Araújo, 2006; Kasiri, Fookes, Sridharan, & Morgan, 2017; Piorkowski, Lees, & Barton, 2011; Soekarjo, Orth, Warmerdam, & van der Kamp, 2019). These techniques have also been more formally classified (using cluster analysis) based on the distinctive spatial patterning's of the end effector (e.g., the fist or foot used to strike a target) made with respect to the struck object (Kasiri et al., 2017; Soekarjo et al., 2019). Indeed, classifying among categories of discrete movement patterns of coordination has been approached in various other tasks including basketball (Rein, Button, Davids, & Summers, 2010), soccer (Chow, Davids, Button, & Rein, 2008), and tennis (Buszard et al., 2017).

Table 1
Notational analysis for obtaining the coordination and control for each strike.

Coordination (body orientation relative to bag)	Coordination (body part)	Control (upper limbs)	Control (lower limbs)
Facing	Left arm	Knuckles	Inner foot
Rear facing	Left leg	Palm	Outer foot
Spin	Right arm	Backfist	Laces
	Right leg	Hammer*	Heel
	Left elbow	Thumb	Shin
	Left knee	Inner wrist^	Calf
	Right elbow	Outer wrist	Point (of knee)
	Right knee	Inner forearm^^	Sole
	Both hands	Outer forearm	
	Head	Point (of elbow/head)	

* = Hammer refers to the edge the hand on the side closet to the small finger; ^ = the distinction between the hand and the wrist was made based on whether the padded part of the glove or the strap part of the glove was used to strike the bag; ^^ = the distinction between the wrist and forearm was made based on whether the strap part of the glove or exposed skin of the forearm was used to strike the bag. NOTE: not all combinations of coordination and control solutions were realized by participants, refer to Fig. 6 in the results section for actions used in the experiment.

Improving the functionality of a coordination solution does not require a fundamental change in the linkages among joints, rather a remaining degree of freedom is parameterized to optimize performance further (e.g., such as internal rotation at the shoulder – see Fig. 4 panels E though H). Different control solutions were therefore, also denoted based on different surfaces of the limb used such as the knuckles, the palm, back of the hand, and side of the hand (Fig. 4, E-H exemplifies these with the left hand). This follows previous work in striking tasks focused on how movement variability at the control levels can improve striking force - including by varying how the limb is used (Bolander, Neto, & Bir, 2009), range of motion (Estevan, Álvarez, Falco, Molina-García, & Castillo, 2011; Estevan, Falco, Álvarez, & Molina-García, 2012; Falco et al., 2009; Kim, Kim, & Im, 2011; Loturco, Artioli, Kobal, Gil, & Franchini, 2014), and foot positioning (Kim, Kwon, Yenuga, & Kwon, 2010; Loturco et al., 2016). Identifying/classifying different control solutions based on movement patterns of coordination has also been approached in a range of other tasks such as tennis (Lee, Chow, Komar, Tan, & Button, 2014), swimming (Komar, Potdevin, Chollet, & Seifert, 2018), and climbing (Herault, Orth, Seifert, Boulanger, & Lee, 2017). Also, for an extensive review related to the functional role of movement variability in striking actions in combat sports see Orth, van der Kamp, and Rein (2018).

2.5.2. Quantifying flexible and persistent creativity and exploration

Linking variability in coordination and control to creativity assumes that creative actions can emerge out of variability in either coordination and control (Orth et al., 2017). As detailed in the introduction, traditionally, flexible creativity is quantified by counting the total number of different, mutually exclusive categories from which solutions emerge (De Dreu et al., 2012; Moraru et al., 2016). This suggests that flexible creativity in the kickboxing task can be quantified by counting the different coordination solutions used to strike the bag. Flexible exploration is, therefore, a quantification of the amount the individual switches among different coordination solutions. Furthermore, traditionally, persistent creativity is measured by the average number of solutions derived from one and the same category. We operationally measured persistent creativity by quantifying the number of different ways each coordination solution varied at the level of control. In the kickboxing task, persistent creativity was measured in terms of the number of different ways the end effector was used to strike the bag. Persistent exploration is, therefore, a quantification of the amount the individual switches among different ways of using an end effector while using the same coordination solution (see Fig. 4, E–H).

2.5.3. Outcome variables

Data (i.e., the labeled coordination and control solutions for each strike and the impact force of each strike) we quantified several traditional creativity indicators as well as to quantify exploration at the levels of coordination and control. Specifically, the notational and impact force data were then used to compute the following indicators (see Table 2 for detailed description of how these are calculated and interpreted):

- **Task achievement indicators**: *task success*, *functionality*.
- **Creativeness indicators:** *fluency*, *flexibility, persistence*, *originality*, and *creativity*.
- **Search indicators**: *right arm use, median bout length*, *exploratory efficiency*, *coordination switching ratio* and *control switching ratio*.

2.6. Statistical analysis

WM group differences were examined using two tailed independent sample t-tests (denoted *t*) for interval data with normal distributions (examined using Kolmogrov-Smirnov tests), otherwise the Wilcoxin rank-sum test (denoted, W_S) was used. Normality tests were also followed up with Levene's test to determine homogeneity of variance and the adjusted degrees of freedom values reported when significant. The Chi-squared test (denoted, X^2) was used to consider group effects on task success as well as to examine (in follow up) the likelihoods of using different limbs to solve the striking task. Bonferroni adjustments were used to correct for multiple comparisons.

Table 2
Outcomes used to assess task success, creativity and search.

Variable	Definition
Task achievement indicators	
Task success	Participants were either successful in achieving their target force or they failed (i.e., gave up and chose to discontinue the experiment).
Functionality	Average force achieved relative to the target threshold over all strikes for a given participant (Lenetsky, Nates, Brughelli, & Harris, 2015).
Creativeness indicators	
Fluency	Calculated as the total number of unique actions used during the striking task across and within coordination and control categories (Moraru et al., 2016).
Flexibility	The total number of different/unique coordination solutions used (Moraru et al., 2016).
Persistence	The average number of control solutions per category of coordination solutions used. Determined as the total number unique actions developed (fluency) divided by the number of coordination solutions (flexibility) (Moraru et al., 2016).
Originality	Number of unique solutions developed combining levels of coordination and control levels of analysis which were statistically uncommon. This required that the action occur < 5% relative to solutions expressed by all participants throughout the experiment (Gillebaart, Förster, Rotteveel, & Jehle, 2013; Kleinmintz, Goldstein, Mayseless, Abecasis, & Shamay-Tsoory, 2014; Simonton, 2003).
Creativity	Solutions that were original (shown by < 5% of participants) and functional (above 90% of target force) (Orth et al., 2017).
Search indicators	
Right arm use	Expressed as a percentage of the right arm used relative to other limbs, was determined to estimate to what extent the participants explored the 'action insight' (Dominowski, 1995; Hristovski et al., 2011).
Median bout length	Median length of bouts made up of consecutive solutions within a coordination category (Moraru et al., 2016).
Exploratory efficiency	Fluency divided by the total number of actions used (expressed as a percentage).
Coordination switching ratio	Number of times a change from one coordination mode to another occurred relative to the total number of actions.
Control switching ratio	Number of times a change from one control mode to another occurred while using the same coordination solution (i.e., at least two coordination solutions occurring in a row) divided by the total number times a control switch could have occurred.

A follow-up exploratory analyses was also undertaken which involved forming groups based on whether or not participants achieved their target force. This involved successful (n = 21) versus unsuccessful (n = 21) group comparisons (i.e., again using independent t-tests and Wilcoxin's rank-sum tests with Bonferroni adjustments and Levene's tests and corrections for any violations in homogeneity of variance).

Effect size *r* was used for t-tests and Wilcoxin rank-sum tests. For independent t-tests this was calculated from the *t*-statistic such that: $r = \sqrt{t^2/(t^2+df)}$, noting that the $df = 40$ (i.e., N-2). For the Wilcoxin rank-sum test effect size *r* was calculated from the *z*-score following, Rosenthal (1991), such that: $r = Z/\sqrt{N}$, noting that $N = 42$. To interpret the effect size *r*, values between 0.1 and 0.3 are considered small, values between 0.3 and 0.5 are medium, and values greater than 0.5 are large. Finally, an interpretable effect size for Chi-squared tests were computed using the odds ratio (for overview of all aforementioned statistical procedures see, Field, 2009).

3. Results

3.1. Number recall, perception of mental strain, and task validation

Significant differences in error arose between the high and low WM load conditions in terms of number recall success, $t(40) = -2.38$, $p < .05$, $r = 0.12$, where the high WM load group were less successful (on average 91%, SD = 10) than the low WM load group (97%, SD = 4). Significant differences were also observed between the high WM load group and the low WM load group for the perception of recall task difficulty for the WM task, where the high WM load group perceived the recall task as significantly more difficult, $t(40) = 2.64$, $p < .05$, $r = 0.39$. A significant difference was also observed between WM conditions for the participants' perception of attention to the number retention during striking, where the high WM group showed a significantly higher level of perceived attention to the number recall task, $t(40) = 2.78$, $p < .05$, $r = 0.40$ (Table 3). Furthermore, the perception of difficulty of the striking task was perceived equally difficult (statistically speaking) between conditions, $t(40) = -0.27$, $p > .05$.

In order to clarify that the task design had good construct validity as a convergent task (where a non-obvious solution was required in order to be successful and that the task promoted a shift away from using the most obvious solution), the limb used for the

Table 3
Statistical analysis results for group differences in performance and perception of the tasks.

	High WM load, Mean (SD)	Low WM load, Mean (SD)
Number recall success (%)	91.6% (10.9)*	97.8% (4.3)
Recall task difficulty perception	2.10 (1.14)*	1.38 (0.50)
Striking task difficulty perception	3.43 (1.21)	3.33 (1.11)
Attention to number recall perception	3.71 (1.55)*	2.48 (1.33)

WM = working memory. SD = standard deviation.
* = indicates a statistical difference ($p < .05$).

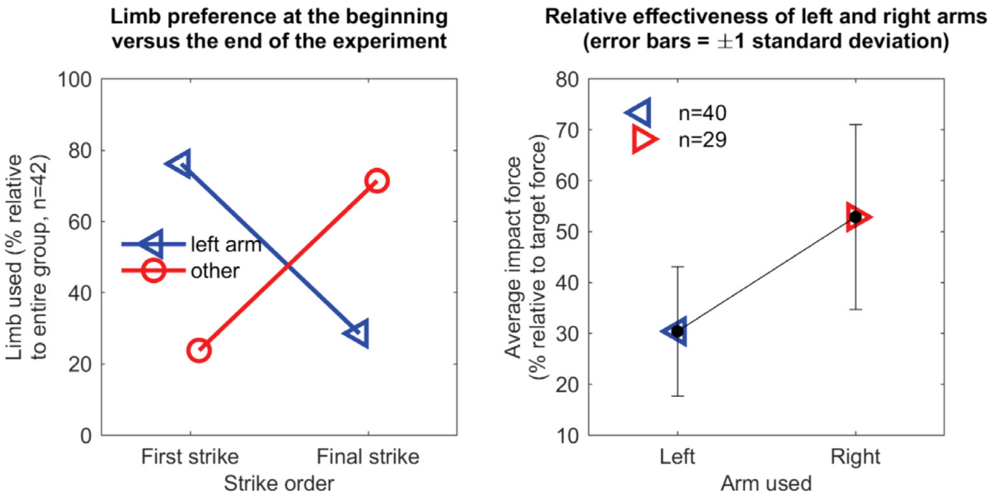

Fig. 5. Construct validity for the convergent doing task. The left graph shows that the first strike was most commonly with the left limb (representing the most obvious solution) and that through practice alternative solutions were explored by about 80% of all participants. The right graph compares the functionality of the left versus right arm showing the manipulation had the desired effect, i.e. to reduce the effectiveness of the left limb relative to the right (note that 29, or 70 percent of, participants used the right arm at some point and 40 participants used their left arm).

first strike across all participants was examined alongside the limb used for the final strike. To this end, the left panel of Fig. 5 shows the percentage use of the left arm relative to all other actions for the first and last strike. The relative functionality (i.e., impact force as a percentage of the goal force) was also determined for the left and right limbs and is presented in right panel of Fig. 5. The right graph indicates that the right limb supported more forceful strikes (note that 29 participants used the right hand across the entire experiment, indicating the solution was not explored by all participants). The left graph shows that most participants started by using their left hand but by the end of the experiment had begun using alternative coordination solutions- indicating that participants were capable of performing alternative actions, an important condition of convergent tasks, (Lin & Lien, 2013).

3.2. *Effect of working memory on task success, search behavior, and creative outcomes.*

Table 4 summarizes the outcomes of planned comparisons between the high and low WM load groups. None of these comparisons for differences were found significant (p's > 0.45) and the observed effect sizes were small (r's < 0.11).

3.3. *Descriptive overview of actions used and the frequency of attempts between high and low working memory load groups*

Fig. 6A shows the frequency distribution in descending order of strikes used and their label (listed and detailed at the bottom right

Table 4
Planned comparisons between high and low working memory (WM) load groups.

	High WM load, Median (IQR), n = 21	Low WM load, Median (IQR), n = 21	*t*-score (t), z-score (z, from Wilcoxin rank-sum tests), or, Chiˆ2 (X^2); p value (p)*; effect size (r), odds ratio (o).
Task achievement indicators			
Task success (yes/no)	9/21	12/21	X^2 = 0.86; p = .36; o = 0.56
Functionality	35.3 (15.7)	43.7 (17.2)	t = 1.54; p = .13, r = 0.24
Creativeness indicators			
Fluency	4 (5)	4 (6)	z = -0.06; p = .96, r = 0.01
Flexibility	3 (2)	2 (2)	z = -0.34; p = .75, r = 0.05
Persistence	2 (0.8)	1.7 (1.0)	z = -0.62; p = .57, r = 0.10
Originality (total)	7	6	z = -0.39; p = .71, r = 0.06
Creativity (total)	5	6	z = -0.35; p = .74, r = 0.05
Search indicators			
Right arm use (%)	29.4 (74.8)	16.7 (63.9)	z = -0.75, p = .45, r = 0.12
Median bout length	2 (2)	2.5 (3.5)	z = 0.09; p = .94,r = 0.01
Exploratory efficiency (%)	7.9 (17.7)	11.5 (18.7)	z = -0.58; p = .49, r = 0.09
Coordination ratio (%)	0.13 (0.34)	0.22 (0.30)	z = -0.49; p = .62,r = 0.08
Control ratio (%)	0.10 (0.28)	0.07 (0.53)	z = -0.20; p = .84,r = 0.03

IQR = interquartile range (25th to 75th quartiles difference). Note: Kolmogrov-Smirnov tests showed only functionality was normally distributed (hence the *t*-statistic is reported for this case). According to Levene's test, functionality showed homogeneity of variance for independent group comparison. * = with Bonferroni correction significance was set at p ≤ 0.004.

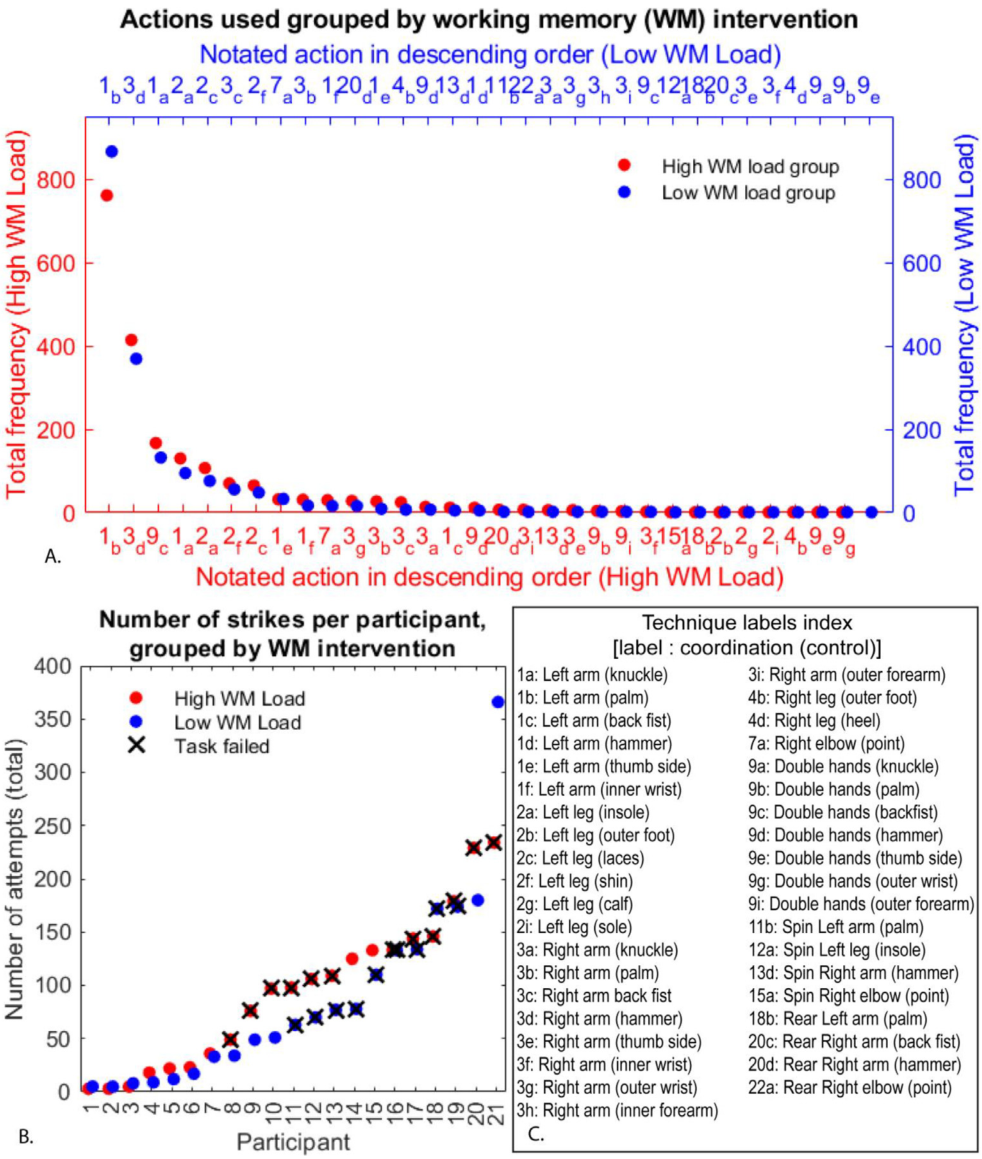

Fig. 6. Overview of the types of actions and the frequency of actions used comparing the high (red) and low (blue) working memory groups. 6A depicts the frequency of all coded actions in descending order of magnitude. 6B shows the total number of strikes used per participant per group. Note the 'x' shows those participants who failed to reach their target force. The corresponding labels of all coded actions shown in 6A are given in 6C.

of Fig. 6). In overview, across the entire experiment a total of 3748 strikes were observed with 39 distinct actions (unique combinations of coordination and control solutions). The most frequently occurring action for both groups was to strike the target while facing it with the palm of the left hand (labeled '1b') – this action occurring a total of 1629 times (44% of actions registered across the entire experiment). The next most frequent action was to strike the target while facing it with the right arm using the small finger side of the hand (i.e., like a hammer: labeled '3_d'). This action was used 794 times (representing 21% of all actions). There were no statistical differences in terms of which action was most frequently used as a function of WM load. Fig. 6B shows how many actions each individual used as a function of WM load where in summary terms the high WM load group showed a median of 98 (interquartile range = 119) and the low WM load group showed a median of 63 (interquartile range = 116) (no significant differences were found between groups, $W_s = 429.5$, $z = -0.55$, $p = .58$, $r = 0.08$).

3.4. Outcomes on task success indicators between high and low working memory load groups

Referring to Fig. 6B (bottom left), this graph indicates which participants failed at the task (indicated with a black cross). Nine individuals failed in the high WM load group and 12 failed in the low WM load group. Level of task success was not statistically different between groups nor was the level of functionality (i.e., average impact force across all strikes) (Table 4).

3.5. Outcomes on creativeness indicators between high and low working memory load groups

There were no significant differences between WM load groups on outcomes for the creativity indicators (see Table 4 and Supplementary Fig. 1). There were also no apparent trends in outcomes based on WM group comparisons. Irrespective of group membership: the fluency outcomes indicate participants developed a median of 4 unique solutions per participant with an inter-quartile range (IQR) = 5; flexibility outcomes show a median of 2.5 coordination solutions were developed per participant (IQR = 2); persistence data reflect a median of 2 control solutions per coordination solution was developed on average per participant (IQR = 0.7); originality data that across all participants 25 original actions were shown (i.e., actions that were common to two or less individuals, noting that this was accomplished across 13 individuals); finally across all participants 11 creative actions were shown (and accomplished by 11 individuals).

3.6. Outcomes on search indicators between high and low working memory load groups

There were no significant differences with respect to the search indicator outcomes between the high and low WM load groups (see Table 4 and for the distribution see Supplementary Fig. 2). As with the creativity outcomes, there were also no apparent trends in outcomes based on WM group comparisons. In overview, independent of group membership: a median of 27.2 percent of actions (IQR = 67.1) were with the right arm; the median bout length showed that actions were used one after the other a median of 2.5 times before switching to another solution (irrespective of whether it was a change in terms of coordination or control); exploratory efficiency indicates that 9.8% (median) of actions were unique (i.e., for every 10 actions participants executed, they developed one new way of striking the bag, irrespective of if this was in terms of coordination or control); the coordination switching ratio showed that for each action executed, 17.8% (median) of these were to switch to a different coordination solution, and; finally the control switching ratio showed that during bouts where the same coordination solution was used, a median of 7% of these involved switching to a different control solution.

3.7. Follow-up comparisons between successful and unsuccessful participants

As there were no significant effects of WM loading on task success, creativity outcomes and search, we carried out additional exploratory analyses. When examining the data in Fig. 6B, it was apparent that participants who struck the bag more frequently were more likely to fail. Indeed, individuals who failed were strongly and statistically more likely to use more strikes (median = 110) compared to those who succeeded (median = 22), W_s = 295.5, z = -3.9, p < .001, r = 0.60). These results led us to contrast search behavior and creativity by considering the role the of task success as an independent variable – these results are summarized to Table 5 and reveal a number of significant differences.

Statistically significant differences between groups formed on the basis of success (n = 21) and task failure (n = 21) were uncovered across functionality, creativeness (summarized to Supplementary Fig. 3A), and exploratory efficiency (summarized to Supplementary Fig. 3B). In terms of functionality, across all actions produced by successful participants, the bag was hit with a mean force of 49.9% (SD = 10.3%), relative to the target force. This was statistically higher than the group that failed (t = 5.7, p < .001, r = 0.67), who showed a mean of 34.1% (SD = 7.5%), relative to the target force. The likelihood of a creative action occurring in the successful group (i.e., who used a total of 10 creative actions) was significantly higher than the unsuccessful group (z = 3.1, p = .002, r = 0.48) (who used a total of 1 creative action). Additionally, exploration efficiency was significantly higher in the successful group

Table 5
Follow-up exploratory comparisons comparing succeed and fail groups on outcome variables.

Variable	Successful group,Median (IQR), n = 21	Unsuccessful group, Median (IQR), n = 21	*t*-score (t), z-score (z, from Wilcoxon rank-sum tests); p value (p)*; effect size (r).
Task achievement indicator			
Functionality#	49.9 (15.8)	34.0 (9.0)	t = 5.7, p < .001, r = 0.67
Creativeness indicators			
Fluency	4 (3)	6 (6)	z = -1.44, p = .15, r = 0.22
Flexibility	2 (2)	3 (2)	z = -0.23, p = .81, r = 0.04
Persistence^	1.3 (1)	2 (0.67)	z = -2.59, p = .01, r = 0.40
Originality (total)	7	6	z = -0.23, p = .82, r = 0.04
Creativity# (total)	10	1	z = -3.1, p = .002, r = 0.48
Search indicators			
Right arm use (%)^	40.0 (60.8)	4.6 (59.8)	z = -2.06, p = .04, =0.32
Median bout length	2 (1.8)	2.5 (5.8)	z = -1.52, p = .13, r = 0.23
Exploratory efficiency (%)#	22.2 (30.2)	5.1 (7.2)	z = -3.99, p < .001, r = 0.62
Coordination ratio (%)^	25.0 (43.2)	13.3 (21.2)	z = -1.94, p = .05, r = 0.30
Control ratio (%)	4.9 (19.6)	10.3 (24.0)	z = -0.97, p = .34, r = 0.15

IQR = interquartile range (25th to 75th quartiles). IQR = interquartile range (25th to 75th quartiles difference). # = Significant comparison. * = with Bonferroni correction significance was set at p < .004. ^ = trending significant.

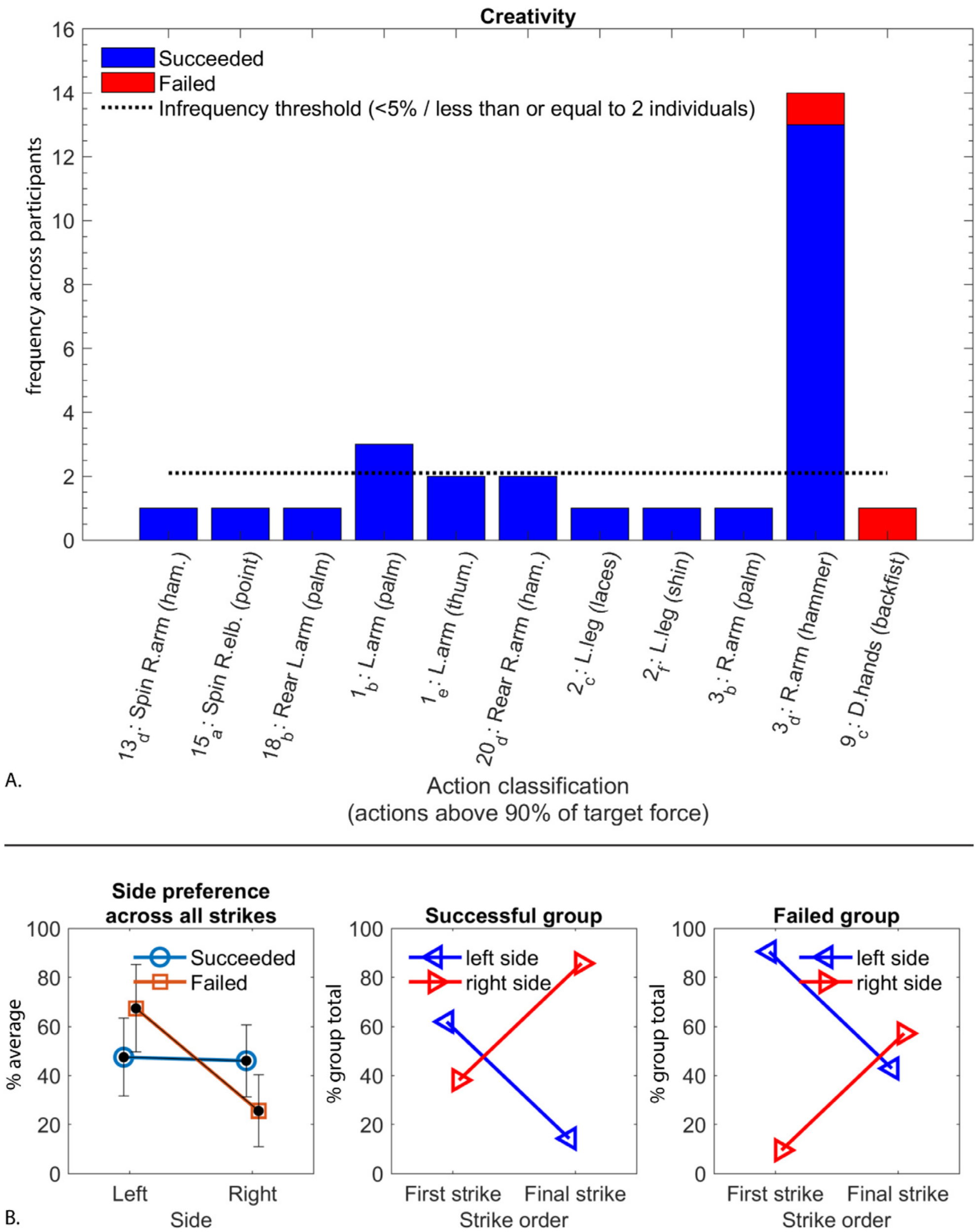

Fig. 7. Creative actions developed by successful and unsuccessful groups (Panel A). Note that only actions with a frequency of occurrence under the threshold line were creative. Panel B compares the side of body preferences for all strikes as well as for the first and last strikes for the successful and unsuccessful groups. Note: **D.** = double; **elb** = elbow; **thum.** = thumb; **ham.** = hammer.

(Mdn of 22.2% new actions relative to the total number of actions used) compared to the unsuccessful group (Mdn = 5.2% new actions relative to the total number of actions used), z = -3.99, $p < .001$, r = 0.62.

Notably, a number of outcomes (persistence, right arm use, coordination switching ratio) also showed trends to significance (i.e., reaching $p \leq 0.05$ but discounted due to Bonferroni adjustment). These trends (which showed moderate to large effect sizes), suggested that participants who succeeded showed less persistence, tended to use their right arm, and tended to more often switch which coordination solution was used.

The fact that the exploration efficiency was higher in the successful group suggests that the faster participants discovered a solution that could produce sufficient force, the more likely they were to succeed. We, therefore, also examined in more detail the creative actions developed (i.e., those which were also highly associated with tasks success) as well as the first and last actions used by participants grouped according to success or failure. Fig. 7A suggests that most of the creative and functional solutions involved the use of the limbs on the right side of the body. Fig. 7B suggests an interaction effect such that the successful group tended to use the left and right side equally, whereas the unsuccessful group preferred to use the left side and were less inclined to use right side solutions. This preference was compounded when comparing groups at the first and last strike. Those who succeeded were 5.8 times more likely to use a limb on their right side from the outset compared to the group that failed (X^2 = 4.73, p = .03). Furthermore, the group that succeeded were 4.5 times more likely to finish the task with a limb on the right side compared to the group that failed (X^2 = 4.2, p = .04).

4. Discussion

This study examined whether cognitive WM resources can be considered a key constraint on search and creative outcomes in a convergent doing task. Following the dual pathway model (Nijstad et al., 2010), we anticipated that when WM is challenged, a reduced persistent exploration and increased flexible search would characterize creative solution development and task success in convergent tasks. However, under the constraints of the current experiment, these predictions were not substantiated. Search and creative outcomes were not related to available WM resources.

4.1. Findings in context with traditional approaches to have examined what degree working memory resources moderate search and creativity

The findings regarding comparisons between the high and low WM load groups are similar to Moraru et al. (2016), in which no difference in search or creativity outcomes were observed in groups with different WM resources in a divergent doing task. The lack of significant differences in our study between groups with different WM resources (at least related to symbolic WM) suggest that WM capacity is not substantively influential in search behavior and creative outcomes in solving or attempting to solve convergent doing problems.

According to the participants' experience, a greater effort was invested when dealing with the high WM load (Table 3). Specifically, all participants in the low WM group reported significantly lower levels of perception of difficulty of the recall task, significantly reduced perception of attention to number recall compared to the high WM load group – which is consistent with previous work that holding five digits strained the cognitive WM resources more so than two (Baddeley, 2003; De Dreu et al., 2012). It is also reasonable to conclude that the set-up of the experiment was successful in creating a convergent task where a specific solution was optimal and facilitated a search for functional and original solutions (at least in the successful participants). This can be observed in Fig. 5, where the predominant technique for the first strike was utilizing the left arm, an obvious solution. Whereas a less obvious solution, utilizing the right arm, was the most functional strike as it produced the most force compared to other limbs across groups. This finding conflicts with cognitive frameworks that suggest success in convergent tasks is facilitated by persistent search (De Dreu et al., 2012; Lin & Lien, 2013). Instead, persistent or flexible search can be more or less functional in solving motor problems depending on the constraints at hand (Orth et al., 2017).

In terms of limitations related to the WM manipulation, it is possible this study had insufficient power to detect the effect of WM manipulations (i.e., the study had sufficient power to detect large effects). Hence, for experiments involving WM manipulations in movement tasks, small effects at best should be expected. In sum, WM load had no clear effect on creative outcomes and search, suggesting that symbolic WM resources are not a critical personal constraint in this task. In the following section we consider reconciling these findings with a perspective where creative action emerges from the interaction of constraints – where, at least in this study, other constrains were much more influential in search behavior and creative outcomes than WM. Granted the strong effects of the initial actions used in solving the motor problem on task success (recall Fig. 7B), we focus on intrinsic dynamics as an alternative hypothetical proposition to that of the role of WM in creative action emergence.

4.2. Creative actions as emerging from the interaction of constraints

In the follow-up exploratory analysis, it was found that successful participants tended to avoid using the left side of their body across trials and were more likely to use the right side at the first strike. On the one hand, the tendency to vary actions with respect to the total number of actions used was also significantly higher in successful participants. On the other hand, participants who failed, tended to persistently/repetitively explore the same coordination solution. Finally, task success was also supported by the use of creative actions which tended to arise from use of the right side of the body. Hence, it would seem that the tendency to avoid using the left limb (which required at least some degree of flexibility in search, noting also that the coordination switching ratio tended toward significance in the successful group) as well as to avoid highly repeated search (i.e., where more persistent outcomes tended to be higher in the fail group), supported the emergence of creative actions and ultimately task success. As the motor task was the same across all participants, this suggests the large differences in the initial actions (or preferences therein) used by successful versus unsuccessful participants can be taken to indicate that the individuals' intrinsic dynamics had an important impact of the search behavior, creative actions, and ultimately, task success/failure (Kostrubiec et al., 2012; Orth et al., 2018; Zanone & Kelso, 1992).

The equipment constraints (i.e., modifying the intrinsic dynamics by making the left hand much weaker with a padded glove) impacted some participants much more than others to induce a tendency to use the limbs on the right side of the body. This supported successful completion of the task and (for most) the performance of the 'action insight' (using the right back-fist action) and for others, the development of original and functional (creative) solutions (such as performing a 'spinning back-fist'). Whereas, participants who failed at the task had a very strong left hand attractor, and showed a significant tendency to develop more control solutions (i.e., indicated in a tendency to produce more persistent outcomes). That is, the results infer that participants who tended to start with the 'wrong action' (i.e., in the wrong location in perceptual motor landscape, Hristovski et al., 2011), needed to be able to able switch to different coordination solutions or avoid developing alternative solutions at the level of control.

In sum, these findings broadly imply the initial conditions (most likely stemming from individual constraints) shaped creative search and outcomes. According to Orth et al. (2018) (see also, Kostrubiec et al., 2012), an important candidate predicting the development of new solutions during learning is the current behavioral repertoire of the individual (i.e., prior to carrying out the given motor problem). For example, in Orth et al. (2018), it was found that in a climbing task, beginners who produced less movement patterns prior to learning, took significantly longer (multiple practice sessions spanning weeks) to significantly improve performance.

4.3. Future research

For future research aiming to better understand creative actions, a more comprehensive examination of individual constraints (in particular examining the current behavioral repertoire) may yield fruitful results (Hristovski et al., 2011; Orth et al., 2017). To address this operationally would require the implementation of a 'scanning procedure' prior to the experiment being conducted to test whether individuals with a broader attractor space are also more efficient in discovering creative solutions. We also expect different approaches and potentially more powerful constraints manipulations might be considered. For example, monitoring search behavior and facilitating where necessary an increase in flexible search may be more effective for inducing creative solution emergence. Indeed, individualized constraints manipulation is an approach that has examples in applied coaching and physical therapy literature (Kal et al., 2018; Orth et al., 2019).

Another approach may be to represent greater variation in constraints during practice, such as by frequently changing available equipment, rules, and tasks (Chow, Davids, Hristovski, Araújo, & Passos, 2011; Lee et al., 2014; Savelsbergh et al., 2010). Alternatively, individuals often search for creative solutions in groups or under competitive constraints - what is the role of interacting with other individuals during this process? Is group diversity (e.g., in terms of culture, skill, age) in some way crucial for the development of creative solutions at the individual level? It might be considered that observing an isolated individual is a special case of how creative outcomes are typically developed. It probably much more common to develop creative solutions in groups (Glăveanu, 2014; Kimmel, Hristova, & Kussmaul, 2018; Orth et al., 2019; Withagen & van der Kamp, 2018). It may also be fruitful to evaluate WM tasks related to recalling actions as opposed to numbers. Another alternative might be to have participants memorize sequences of actions. For instance, instead of numbers, actions might 'interfere' with the process of recalling prior explored actions to a larger extent than number memorization.

Finally, another concern is how to more effectively quantify exploration. A key challenge being to develop insights into how exploration strategies may underpin creative action emergence (or at least successful learning and performance, Gel'fand & Tsetlin, 1962; Orth et al., 2018; Pacheco et al., 2017). In doing so, methods should be further explored for providing low dimensional data that allows to more objectively assess shift between or within strategies – for instance deploying machine learning approaches to classify changes at coordination (Kasiri et al., 2017; Rein, Davids, & Button, 2010; Soekarjo et al., 2019) and control levels (Komar et al., 2018; Lee et al., 2014). Following this, various time-series analysis methods can then be considered toward developing insights into how exploration strategies may underpin creative action emergence and successful learning processes.

For example, qualitative alternation of several actions can be investigated by state transition diagram analysis which can provide an indication into breadth of exploration at the level of coordination (Yamamoto et al., 2013). The influence of constraints on search dynamics has also been operationalized by fractal analysis (Nonaka & Bril, 2014; Van Orden, Kloos, & Wallot, 2011) which reveals the degree to which motor fluctuations (exploration) correlate over-time scales of different length (Stephen, Arzamarski, & Michaels, 2010). Long-range correlation properties of fluctuations describe (mathematically) interdependency from one action the other; or the interdependency of one action relative to previous actions (Nonaka & Bril, 2014; Stephen, Arzamarski, & Michaels, 2010). Low and high interdependency indicates a search in a broad or narrow coordination space, respectively (Nonaka & Bril, 2014). Each approach might characterize how individual and social constraints affect search dynamics, and affects creative action emergence (Marmelat & Delignières, 2012; Nonaka & Bril, 2014). A modified task set-up, however, may be necessary to yield long enough time-series for the above-mentioned analyses (Stergiou, 2004).

In any case, adapting the above-mentioned methods needs to balance one of the key recommendations in Orth et al. (2017) to ensure 'appropriate complexity or difficulty needs to be embodied in the constraints upon action for creative motor action to emerge.' (p.5). In doing so, representative task design is an approach that advocates the use of research vehicles adapted from contexts of sport, in part, because these can improve the generalizability between research tasks and tasks of daily living (i.e., where a key indicator of generalizability between two settings is exploration and functional movement variability) (for a broader discussions see, Araújo, Davids, & Passos, 2007; Davids, Button, Araújo, Renshaw, & Hristovski, 2006; Dicks, Button, Davids, Chow, & van der Kamp, 2017; Dunwoody, 2006; Orth et al., 2019). In these respects, the task vehicle presented in this study has many aspects of interest toward contributing to future research.

5. Conclusions

Taken broadly, the findings in this experiment run counter to the notion that creativity arises from shear number of attempts, and instead, suggest that the emergence of creative actions may be related to the initial approach to the task, as well as the motor strategy of actively switching actions during solution search. Wherein learner's that actively switched qualitatively to different patterns of limb coordination or use of each limb tended to find a more functional (effective) outcomes. This latter point is favored in that creative actions were in some way a product of the tendency to vary actions more frequently relative to the overall number of actions used in the effort to solve experimental task constraints, as well as the finding that unsuccessful participants tended to repeatedly search the same coordination solution.

The current study suggests that working memory capacity is not a pertinent constraint on search and creative outcomes in a convergent doing task. These results also contrast with cognitive research by showing that persistent/repeated search was not beneficial in a convergent task. Specifically, participants naïve to (combat sport) striking tasks utilizing a flexible search strategy were more likely to develop creative solutions to address a convergent doing task. We argue that the interaction among constraints, and particularly intrinsic dynamics, supported task success on the basis of different limb preferences and a tendency to explore different coordination solutions. As opposed to creative actions being explained by activities of a particular cognitive system, the emergence of creative actions are better characterized as a product of search under interacting constraints.

In sum, our alternative viewpoint of working memory therefore relates to how actions/information of longer times scales impact current search behavior. Metaphorically this might be depicted with deeper values in the intrinsic dynamics landscape. Different individuals are in some way attuned to different time scales or have different couplings with these longer timescales (reflecting what typically is considered individual differences in WM capacity). These differences then manifest themselves in terms of search behavior or the structure in movement variability therein.

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Appendix A. Supplementary data

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